2011

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Keywords
CGC, particle correlations, relativistic heavy ion collisions

Available online at www.sciencedirect.com
ScienceDirect
Nuclear Physics A 00 (2010) 1–4
NUCLEAR PHYSICS A
www.elsevier.com/locate/nuclphysa

Rapidity and centrality dependence of azimuthal correlations in high energy d+Au collisions

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Abstract

We discuss azimuthal correlations in *dAu* collisions at different rapidities and centralities and argue that experimentally observed depletion of the back-to-back bump can be quantitatively explained by gluon saturation in the Color Glass Condensate of the Gold nucleus.

Keywords:

1. Introduction

In a pioneering paper [1] it was proposed to study the azimuthal correlations of hadrons produced at large rapidity separation $\Delta y \gg 1$. The idea is that such correlations are mediated by the BFKL Pomeron. Therefore, unlike hadron production in hard collisions, where there is strong back-to-back correlation at opening azimuthal angle $\Delta\phi = \pi$, correlations in the CGC should be significantly reduced. It has been suggested in [2] that correlations at small Δy in the forward direction can also be used to study CGC. Indeed, forward direction corresponds to small x of nucleus where the CGC effects are strongest. They reduce both single and double inclusive hadron production and thus back-to-back correlations are suppressed. Unfortunately, there is a technical problem: the relevant scattering amplitudes are well-known in the so-called Multi-Regge-Kinematics $\Delta y \gg 1$, which is not applicable in this case. One therefore has to rely on phenomenological models, which offer descriptions that are analytically accurate only in parts of the interesting kinematic region. There are two such approaches: one that is based on the dipole model [2, 3] and another one that is based on the k_T-factorization [4].

The present calculation, based on 'k_T-factorization', assumes that $2 \to n$ process and the two-point correlation functions of CGC fields can be factored out. In this approximation, the $2 \to 4$ amplitudes were calculated for an arbitrary Δy (quasi multi-Regge kinematics, QMRK) in [5, 6, 7, 9] for $gg \to ggq\bar{q}$ and in [8, 10, 11] for $gg \to gggg$ processes. Although generally k_T-factorization fails in the gluon saturation region, there are valid reasons to believe that it provides a *reasonable approximation* of the observed quantities. Indeed, it was proved that k_T-factorization provides the exact result for the cross section for single inclusive gluon production in the leading logarithmic approximation (LLA) (4) [13] (though there is a subtlety in the definition of the unintegrated gluon distribution φ [13, 12]). Although k_T-factorization fails for the double-inclusive heavy quark production, the deviation from the exact results is not large at RHIC energies [14]. At transverse momenta of produced particles much larger than Q_s, k_T-factorization rapidly converges to the exact results. There are also numerous indications that k_T-factorization is phenomenologically reliable (see [4] for examples).

2. Correlations at $|y_T - y_A| \lesssim 1$

First, we would like to consider correlations at small rapidity separations. Azimuthal correlation function is defined as

$$C(\Delta\phi) = \frac{1}{N_{\rm trig}}\frac{dN}{d(\Delta\phi)}\,, \tag{1}$$

where $dN/d(\Delta\phi)$ is the number of pairs produced in the given opening angle $\Delta\phi$ and $N_{\rm trig}$ is the number of trigger particles. The number of pairs is given by

$$\frac{dN}{d(\Delta\phi)} = 2\pi\int dk_T k_T\int dy_T\int dk_A k_A\int dy_A\left(\frac{dN_{\rm trig}}{d^2k_T dy_T}\frac{dN_{\rm ass}}{d^2k_A dy_A}+\frac{dN_{\rm corr}}{d^2k_T dy_T\, d^2k_A dy_A}\right) \tag{2}$$

where $\underline{k}_T$ and y_T are the transverse momentum and rapidity of the trigger particle and $\underline{k}_A$ and y_A are the transverse momentum and rapidity of the associate one. We denote $k_T = \sqrt{\underline{k}_T^2}$ etc. throughout this paper. The first term on the r.h.s. of (2) corresponds to gluon production in two different sub-collisions (i.e. at different impact parameters) and therefore gives a constant contribution to the correlation function, whereas the second term on the r.h.s. describes production of two particles in the same sub-collision. The number of the trigger particles is given by

$$N_{\rm trig} = 2\pi\int dk_T k_T\int dy_T\,\frac{dN_{\rm trig}}{d^2k_T dy_T}\,. \tag{3}$$

Expression for the single inclusive gluon cross section is well-known (see e.g. [13]). The corresponding multiplicity reads

$$\frac{dN}{d^2k\,dy} = \frac{2\,\alpha_s}{C_F\,S_\perp}\frac{1}{k^2}\int d^2q_1\varphi_D(x_+,q_1^2)\,\varphi_A(x_-,(\underline{k}-\underline{q}_1)^2)\,. \tag{4}$$

In the center-of-mass frame $x_\pm = \frac{k}{\sqrt{s}}\exp\{\pm y\}$. Equation (4) is derived in multi-Regge kinematics (MRK) $x_\pm \ll 1$.

The correlated part of double-inclusive parton multiplicity is given by

$$\begin{aligned}\frac{dN_{\rm corr}}{d^2k_T\,dy_T\,d^2k_A\,dy_A} &= \frac{N_c\,\alpha_s^2}{\pi^2\,C_F\,S_\perp}\int\frac{d^2q_1}{q_1^2}\int\frac{d^2q_2}{q_2^2}\,\delta^2(\underline{q}_1+\underline{q}_2-\underline{k}_T-\underline{k}_A)\\ &\quad\times\varphi_D(x_1,q_1^2)\,\varphi_A(x_2,q_2^2)\,\mathcal{A}(\underline{q}_1,\underline{q}_2,\underline{k}_T,\underline{k}_A,y_T-y_A)\,,\end{aligned} \tag{5}$$

where $x_{1,2} = (k_T e^{\pm y_T} + k_A e^{\pm y_A})/\sqrt{s}$. The amplitude $\mathcal{A}$ was computed in the quasi-multi-Regge-kinematics (QMRK) in [8, 9, 10] and recently re-derived in [11] (the $gg \to ggq\bar{q}$ part was calculated before in [5, 6, 7]). In QMRK one assumes that $x_1, x_2 \ll 1$, but Δy is finite. Explicit expression for $\mathcal{A}$ can be found in [10].

For numerical calculations we need a model for the unintegrated gluon distribution function φ. In spirit of the KLN model [15] we write

$$\varphi(x,q^2) = \frac{1}{2\pi^2}\frac{S_\perp C_F}{\alpha_s}\left(1-e^{-Q_s^2/q^2}\right)(1-x)^4\,. \tag{6}$$

where the saturation scale of nucleus is $Q_s^2 = A^{1/3}Q_{sp}^2$, with Q_{sp}^2 the saturation scale of proton fixed by fits of the DIS data. The coupling constant is fixed at $\alpha_s = 0.3$.

It has been pointed out in [10] that due to $1 \to 2$ gluon splittings the double-inclusive cross section has a collinear singularity at $\hat{s} \to 0$, i.e. it is proportional to $[(\Delta y)^2 + (\Delta\phi)^2]^{-1}$. Such singularities are usually cured at higher orders of perturbation theory. Additional contributions to the small angle correlations arise from various soft processes including resonance decays, hadronization, HBT correlations etc. Because the small angle correlations are beyond the focus of the present paper we simply regulate it by imposing a cutoff on the minimal possible value of the invariant mass $\hat{s}$. This is done by redefining the amplitude as $\mathcal{A} \to \mathcal{A}\,\hat{s}/(\mu^2+\hat{s})$. For each kinematic region, parameter μ is fixed in such a way as to reproduce the value of the correlation function in pp collisions at zero opening angle $\Delta\phi = 0$.

k_T-factorization is known to give results that are in qualitative agreement with a more accurate approaches, but miss the overall normalization. Therefore, in order to correct the overall normalization of the cross sections we multiply the single inclusive cross section (4) by a constant K_1 and the double-inclusive one (5) by a different constant

K_2 [16, 17]. The correlation function C depends on both K_1 and K_2. However, the difference $C_\Delta = C(\Delta\phi) - C(\Delta\phi_0)$ depends only on the ratio K_2/K_1. We choose $\Delta\phi_0$ in such a way that $C(\Delta\phi_0)$ is the minimum of the correlation function. This is analogous to the experimental procedure of removing the pedestal [18]. The overall normalization of the correlation function K_2/K_1 – which is the only essential free parameter of our model – is fixed to reproduce the height of the correlation function in pp collisions.

The results of the numerical calculations are shown in Fig. 1–3. In these figures we observe suppression of the bak-to-back correlation in dAu as compared to the bak-to-back correlation in pp, in agreement with the experimental data. In Fig. 3 we also see the depletion of the back-to-back correlation as a function of centrality. Note, that at the time of publication the precise centrality classes of the *data* shown in the lower row of Fig. 3 were not known.

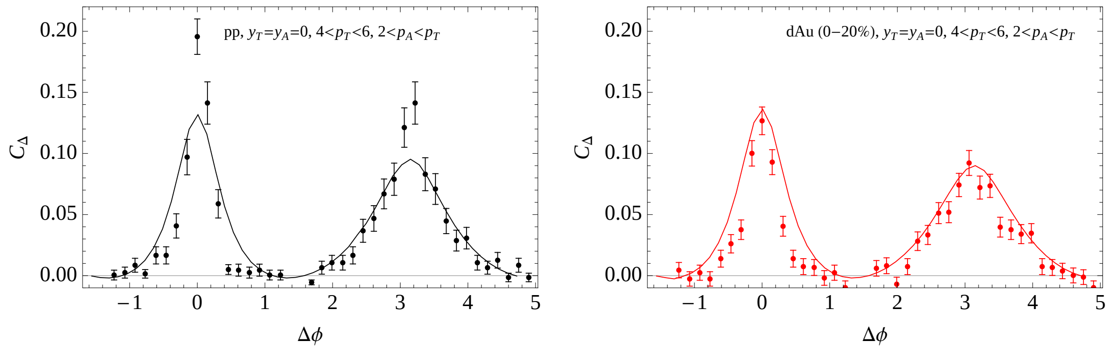

Figure 1: Correlation function at central rapidity. Kinematic region is $4 < p_T < 6$, $2 < p_A < p_T$ (all momenta are in GeV), $y_T = 3.1$, $y_A = 3$. Left (right) panel: minbias pp (dAu) collisions. Data from [18].

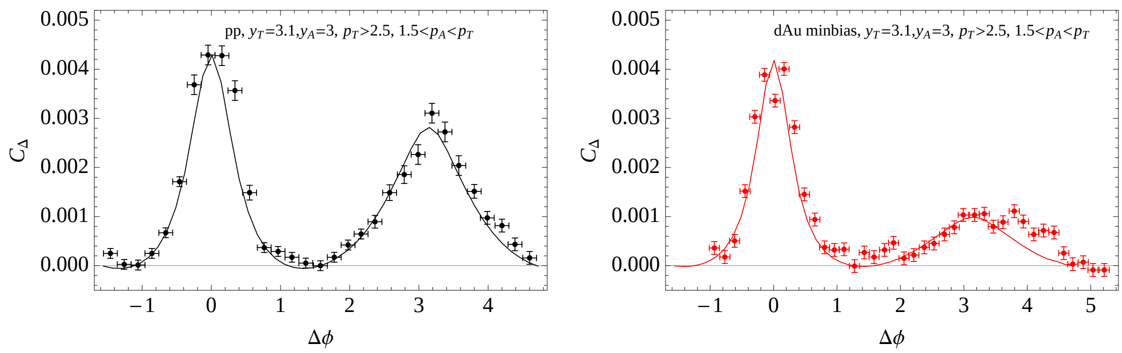

Figure 2: Correlation function at forward rapidities. Kinematic region is $p_T > 4$, $1.5 < p_A < p_T$ (all momenta are in GeV), $y_T = 3.1$, $y_A = 3$. Left (right) panel: the minbias pp (dAu) collisions. Data from [19].

In addition to $gg \to gggg$ and $gg \to ggq\bar{q}$ processes that we took into account in this section, production of valence quark of deuteron $gq_v \to gq_v gg$ gives a sizable contribution at forward rapidities due to moderate value of x associated with deuteron ($x \approx 0.2$ for $p_T = 2$ GeV at $y = 3$). Contribution of this process to azimuthal correlations was analyzed in [2] in the framework of the dipole model in MRK. However, the corresponding expression in k_T-factorization in QMRK is presently unknown thus preventing us from taking it into account in our calculation. In-spite of this we believe that the general structure of the correlation function as well as its centrality dependence is not strongly affected by the valence quark contribution. We plan to address this problem elsewhere.

Acknowledgements

This work was supported in part by the U.S. Department of Energy under Grant No. DE-FG02-87ER40371.

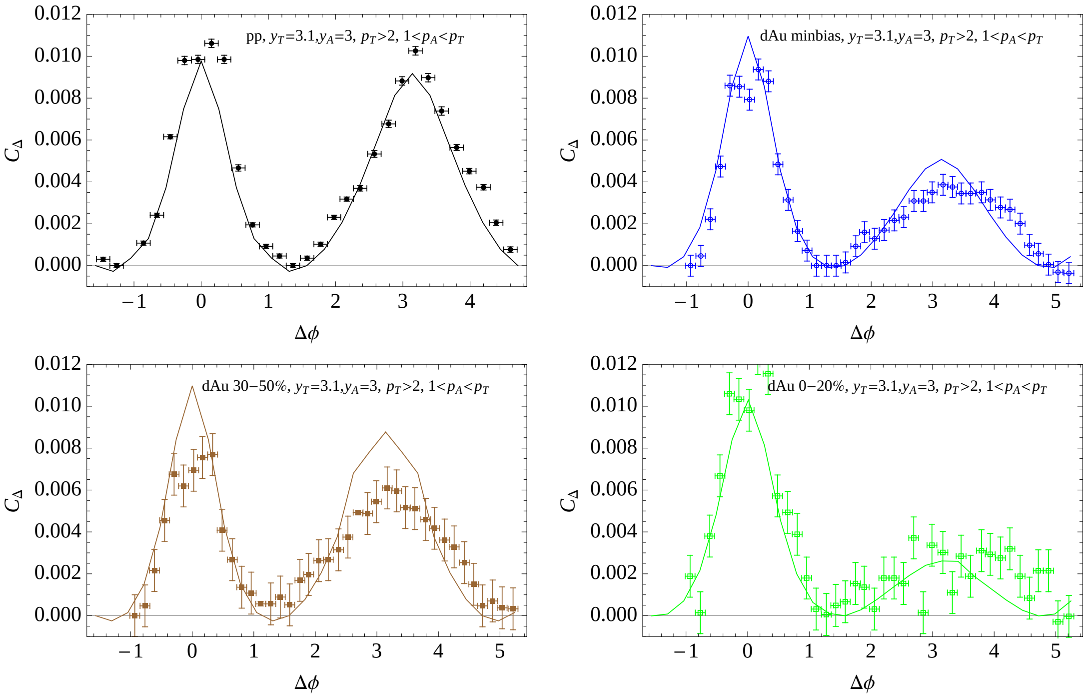

Figure 3: Correlation function at forward rapidities. Kinematic region is $p_T > 2$, $1.5 < p_A < p_T$ (all momenta are in GeV), $y_T = 3.1$, $y_A = 3$. Upper left (right) panel: minbias pp (dAu) collisions. Lower left (right) panel: peripheral (central) dAu collisions. Note: centrality of the theoretical calculation may not coincide with the centrality of the data (the former is not yet known at the time of publication). Data from [19].

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